FOOD SCIENCE AND TECHNOLOGY

FOOD BYPRODUCTS

Valorization Through Nutraceutical Production

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Food Science and Technology

Food Byproducts: Valorization Through Nutraceutical Production
Sandra Teresita Martín-del-Campo, PhD,
Anaberta Cardador-Martínez, PhD
and Jessica del Pilar Ramírez-Anaya, PhD (Editors)
2023. ISBN: 979-8-88697-612-0 (Hardcover)
2023. ISBN: 979-8-88697-876-6 (eBook)

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DOI: https://doi.org/10.52305/LIXJ7605

Library of Congress Cataloging-in-Publication Data

Names: Teresita Martín-del-Campo, Sandra, editor. | Cardador-Martínez, Anaberta, editor. | Del Pilar Ramírez-Anaya, Jessica, editor.
Title: Food byproducts : valorization through nutraceutical production / editors, Sandra Teresita Martín-del-Campo, PhD, Independent consultant, Food Chemistry, Mexico, Anaberta Cardador-Martínez, PhD, Professor, Tecnologico de Monterrey, Campus Querétaro, México, Jessica del Pilar Ramírez-Anaya, PhD, Researcher, Food Sciences and Technology, University of Guadalajara, Mexico.
Description: New York : Nova Science Publishers, [2023] | Series: Food science and technology | Includes bibliographical references and index. |
Identifiers: LCCN 2023021197 (print) | LCCN 2023021198 (ebook) | ISBN 9798886976120 (hardcover) | ISBN 9798886978766 (adobe pdf)
Subjects: LCSH: Food industry and trade--By-products. | Food industry and trade--Waste minimization.
Classification: LCC TP373.8 .F63 2023 (print) | LCC TP373.8 (ebook) | DDC 664/.08--dc23/eng/20230516
LC record available at https://lccn.loc.gov/2023021197
LC ebook record available at https://lccn.loc.gov/2023021198

Published by Nova Science Publishers, Inc. † New York

Contents

Preface

An important volume of byproducts is produced during the harvesting, distribution, and industrialization of fruits, vegetables, cereals, pseudocereals or animal origin raw materials. Byproducts such as food with low-quality standards, seeds, peels, hulls, pulps, serum, among others, have different physicochemical properties and compositions depending on the properties of their origin.

During harvesting and distribution, some products are discarded since they do not accomplish with countries' regulations for human consumption, but others are discarded because they do not fulfill the marked requirements of size, shape, color, etc. or because the market price has fallen to nonprofitable levels. There are no exact numbers about the amount of food lost or wasted. The FAO estimate that one-third of food world production is lost or wasted.

As a result of the industrial transformation of superfoods, the peels, seeds, hulls, some pulp, and serum are discarded since they are not part of the final product due to their characteristics or must not be present due to regulations, depending on the commodity and the different countries regulations. Additionally, wastewater represents an important and underestimated byproduct.

The produced byproducts are often discarded, losing important compounds and additionally producing pollution issues. Often the byproducts are discarded in terrains, rivers, or incinerated. Even though these byproducts are organic and biodegradable, depending on the nature of the original food and the volume discarded, different phenomena could be observed where the byproducts are placed, such as eutrophication, soap formation, acidification, and salinization, as well as greenhouse gas production.

On the other hand, since these byproducts could present similar or higher concentrations of important nutrients and bioactive compounds than the original food, they could be recovered to produce new items that could be used for restitution, enrichment, or development of new products developed to present specific nutraceutical properties. Some recovered compounds could also be used in the cosmetic and pharmaceutical industries. Valorization of food byproducts could help to decrease food waste and pollution.

Using byproducts to produce other higher-value products could be important to the UN 2030 agenda for Sustainable Development. Valorization of byproducts and wastewater has the potential, among others, to contribute to reducing per capita food waste (SDG Target 12.3), improve nutrition by providing nutrients and secure additives to be used in foods (SDG 2), as well as reducing the environmental impact by reducing the tons of organic materials discarded (SDG 6, SDG 13, and SDG 15).

This book shows information about the various byproducts obtained from the harvesting and industrialization of the different superfoods previously mentioned. It is addressed the different bioactive and nutritive compounds that could be recovered from each byproduct.

Different recovery and stabilization processes adapted for each compound are also presented. Finally, some applications for the obtained products are proposed.

The book focuses on superfoods byproduct valorization and is divided into three sections. In the first section, the valorization of selected fruits is reviewed. In the second section, the emphasis is on foods such as cereals, pseudocereals, and legumes. Finally, in the third section, the revision focus on animal origin products.

Section 1. Fruits

Chapter 1

Avocado Byproducts as a Source of Functional and Nutraceutical Compounds

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Abstract

Due to the adverse environmental impact, agroindustrial residues have been a focus of interest. Fruits and vegetable wastes are usually discarded or underused despite the vast reports regarding their use as a source of high-value compounds with beneficial properties for health. The revalorization of these materials depends on the technological approaches suitable to improve sustainability and reduce environmental issues in an economically feasible manner. The production of avocados has constantly been increasing due to the progressive higher demand for this fruits whose processing generates large amounts of residues. Due to its content of valuable bioactive compounds, byproducts such as seeds,

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In: Food Byproducts
Editors: S. Teresita Martín-del-Campo, A. Cardador-Martínez and J. del Pilar Ramírez-Anaya
ISBN: 979-8-88697-612-0

peels, wastewater, and pomace are investigated for producing functional and nutraceutical ingredients and food products. By this means, using avocado waste materials to develop new ways to improve health is relevant to minimizing waste disposal and, thus, the environmental impact as a strategy to promote the circular economy and sustainability of the avocado industry.

Keywords: seed, peel, pomace, wastewater, extraction methods, delivery technologies

Introduction

Avocado is a dicotyledonous tropical plant from the Lauraceae family, which includes 50 genera and 2,500 to 3,000 species. Some of them are commercially relevant as laurel and cinnamon; however, the avocado is the member with the most significant commercial impact worldwide (Schaffer, Wolstenholme, and Whiley 2013). The avocado origin is fixed in Mesoamerica but currently grows under cultivation conditions around the world; Barrientos-Priego and López-López (2000) considered that avocado fruit appeared 12,000 years ago. There is archeological evidence of cotyledons found in the Coaxcatlan cave in Tehuacan, Mexico, dated from 8,000 B.C. and 7,000 B.C. Avocado figured among the main foods of Mesoamerican populations; in the years 200 B.C to 600 A.C. there were populations called Ahuacatlan dedicated to the cultivation of avocado (Téliz-Ortiz and Marroquín-Pimentel 2007). The emergence of different avocado varieties is linked to commerce in pre-Columbian America. With the arrival of Spaniards to America, avocado extended to Cuba and Jamaica, whit the first record in 1657, while in Europe, the first tree was found in 1601. However, the crop arrived late in the United States of America until 1871, when was done the first seed recollection; from this moment, the avocado industry started its development. This development led to the creation of new featured varieties more adapted to various environmental conditions (Schaffer, Wolstenholme, and Whiley 2013).

Avocado fruits are described as a berry with a single large seed; they can be round, elongated, or pear-shaped, and the size depends on the variety, metabolism, and cultivation practices, reaching weights from 50g to 2 kg. On average, 18 to 31% of the total weight are, respectively, peel and seed; the rest of the fruit is edible pulp or mesocarp. The peel or exocarp may be green, yellow, brown, or purple, have a waxy cuticle, and have a single-layered epidermis. The mesocarp consists of parenchymal tissue with a buttery consistency; a high quantity of oil is stored in its vacuoles and specialized storage cells called idioblasts. The seed parenchymal cells store starch, proteins, or oil; 50% of this oil and the reserve nutrients are present in the embryo (Wang, Bostic, and Gu 2010, Chanderbali et al. 2013, García-Fajardo, Ramos-Godínez, and Mora-Galindo 1999).

According to the Food and Agricultural Organization (FAO 2022), avocado is grown under cultivation conditions in 68 countries around the five continents. The world production in 2020 reached more than 8 million tons harvested in a total of 825,532 Ha. That year, Mexico, Colombia, Dominican Republic, and Peru produced 56.3% of the world total, with the former contributing 29.3%.

Avocado fruit is mainly consumed fresh; therefore, industrialization is based on surplus production of fresh fruit (García-Fajardo, Ramos-Godínez, and Mora-Galindo 1999). In countries such as Mexico, the volume of avocado for industrial uses is limited to 16% of the

fruit production (Secretaría de Economía 2012). During the last years, industrial applications have been developed for the extraction of avocado oil, elaboration of processed food such as purees, guacamole, frozen, dried products, cosmetic, personal care, and nutraceutical products (Ramírez-Anaya et al. 2021). During food production and transformation, a certain proportion of the food is lost or wasted; according to Gustavsson et al. (2013), food wastes are those food losses of quality and quantity by the supply chain process taking place during production, postharvest, and processing stages (Rguibi 2021). In this context, the primary cultivation for the production of fresh avocado fruits generates agricultural waste such as biomass in the form of leaves and branches, while the industrial processing of avocado leads to a large volume of seeds and peels in a proportion of 21 to 30% of the processed raw material (Kosińska et al. 2012); other residues are those from avocado oil industry namely wastewater and pomace (Permal, Chang, Seale, et al. 2020).

The efficient use of agricultural and industrial byproducts is essential due to environmental concerns that contribute to ecological, social, and economic sustainability. Therefore, the reduction of food waste and its valorization have become a topic of increasing research interest over the past years and have become an issue of political priority all over the world (Kringel et al. 2020, Aysu and Durak 2015). In the case of avocado, it is recognized that the waste materials from fruit production and industrialization have a high commercial potential as raw materials for producing commodities for food, pharmaceutical, and cosmetic use (Figure 1).

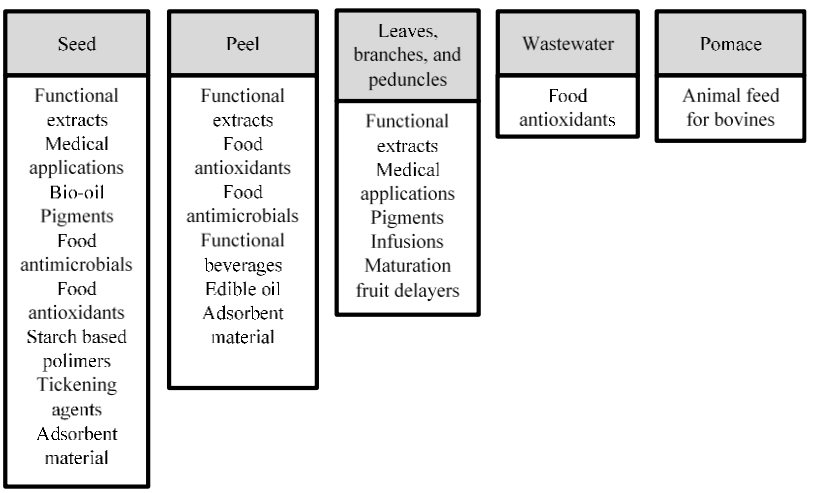

Figure 1. Actual and potential uses of avocado byproducts.

This potential originates from their chemical composition and biological properties. The main components of avocado byproducts are carbohydrates that can be used as functional ingredients and also to make biodegradable polymers, as drug delivery systems, or for the production of food packaging materials (Dávila et al. 2017); high-quality fats or extracts with high biofunctional power are also obtained (Araújo et al. 2018). But it is by far that the production of extracts has been the main focus of interest since it is based on the recovery of bioactive molecules, which sometimes are in higher content in residues than in the edible fraction of the fruits (Colombo and Papetti 2019). In the case of avocado, those molecules consist of pigments, arabinogalactans, a wide diversity of polyphenolic compounds, sterols, terpenoids, and acetogenins, among others; which show properties such as larvicidal,

insecticide, antimicrobial, antifungal, inhibition of different viruses; and health benefits as an antioxidant, proapoptotic, neuroprotector, immunomodulatory, anti-inflammatory, antithrombotic; and auxiliary in the reduction of diabetes, hypertension, and dyslipidemic conditions.

Also, contribute to the reduction of lipid and protein deterioration in foods. However, although those compounds can be successfully exploited, their use in food production is limited by challenges arising from their technological properties during extraction and isolation (Wang, Bostic, and Gu 2010, Figueroa et al. 2018a, Ge et al. 2017, Leite et al. 2009, Oliveira et al. 2019, Salinas-Salazar et al. 2017, Figueroa et al. 2018b).

Composition of Avocado Byproducts

Seed

The seed represents 14-24% of the total weight of the fruit. This structure has a composition of 56% moisture, 2-7% protein, 2-14% lipids, 32-36% carbohydrates, 1.8-2.43% soluble sugars, and 3-6% fiber. Among the minerals are sodium, magnesium, potassium, calcium, manganese, iron, copper, and zinc (Ge et al. 2017). The fiber comprises soluble hemicelluloses, pectins, cellulose, and insoluble hemicelluloses. Content of essential amino acids in the seed protein is adequate compared to the levels in egg albumin (Table 1), outstanding leucine, threonine, tryptophan, and histidine, whose contents exceed or equal those of egg albumin (Ferreira da Vinha, Moreira, and Barreira 2013, Flores et al. 2019, Bressani, Rodas, and Ruiz 2009, Barbosa-Martín et al. 2016, Ceballos and Montoya 2013).

Table 1. Amino acid content in avocado seed

Amino acid	Avocado seed (g/100 g protein)[a]	Egg albumin (g/100 g protein)[b]
Valine	5.0-6.79	7.78
Isoleucine	3.57-4.78	5.69
Threonine	3.34-5.09	5.29
Tryptophan	0.45-1.96	1.75
Phenylalanine	5.05-5.44	6.78
Leucine	6.93-9.15	1.02
Lysine	5.81-8.73	9.53
Methionine	1.73-2.58	4.54
Histidine	1.99-2.60	2.40
Cysteine	1.14-1.53	3.80
Tyrosine	2.66-3.12	4.35
Aspartic acid	9.52-11.91	12.42
Serine	5.11-6.27	8
Glutamic acid	11.76-13.96	16.44
Proline	4.70-5.69	4.61
Glycine	4.75-6.12	3.94
Alanine	5.27-7.66	6.67
Arginine	6.20-7.56	6.45

[a]Bressani, Rodas, and Ruiz (2009), [b]USDA (2021).

The lipids found in the avocado seed are mainly neutral lipids (77.1-80.3%), followed by glycolipid (12.0-13.2%) and phospholipid (7.4–10.9%) fractions. The main neutral lipids are triacylglycerols, followed by mono- and diacylglycerols. Also are found free sterols, fatty acids, and sterolesters. The glycolipid fraction includes monogalactosyl-diacylglycerol (56.3-57.7%), acylsterylglucoside (17.5-18.6%), steryl glucoside (10.1-10.8%) and cerebroside (9.8-10.7%). While phospholipidic fraction include phosphatidylethanolamine (31.3-31.9%), phosphatidylcholine (28.9-31.7%) phosphatidic acids (14.5-17.6%) and phosphatidylglycerol (10.5-13.4%), among others (Takenaga et al. 2008). Of the main fatty acids in the seed lipids in decreasing order of abundance are linoleic ($C_{18:2}$), palmitic ($C_{16:0}$), oleic ($C_{18:1}$), and linolenic ($C_{18:3}$) acids; followed by other less abundant such as pentadecanoic ($C_{15:0}$), palmitoleic ($C_{16:1}$), margaric ($C_{17:0}$), lignoceric ($C_{24:0}$), behenic ($C_{22:0}$), and stearic ($C_{18:0}$) among others. Saturated fatty acids (SFA) constitute around 32.45%, monounsaturated (MUFA) 20.71%, and polyunsaturated (PUFA) 46.72%. Its concentrations vary widely depending on the avocado fruits' maturation, variety, and geographical distribution (Bora et al. 2001, De Sousa Galvão, Narain, and Nigam 2014).

Other apolar compounds in the seed are polyhydroxylated fatty alcohols being identified five; the most abundant are 1-acetoxy-2,4-dihydroxy-hepta-dec-16-ene and 1-acetoxy-2,4-dihydroxy-heptadec-16-yne accounting for 32 and 53.8%, respectively; the other three sum the remaining 14.2%. It has been postulated that avocado seed polyhydroxylated fatty alcohols can play an essential function as a photoprotective agent in UV-induced skin damage. Introducing these compounds to keratinocytes exerts a protective effect against UVB exposure, increasing cell viability, decreasing the secretion of IL-6 and PGE_2, and enhancing DNA repair (Rosenblat et al. 2011). Carotenoids are fat-soluble bioactive compounds with antioxidant and pro-vitamin A activity. Avocado seeds contain lower carotene concentrations than those reported in pulp, reaching values between 1.98 to 2.02 mg/100 g (Ge et al. 2017), including lutein and β-carotene (Bressani, Rodas, and Ruiz 2009). Tocopherols are organic compounds with vitamin E activity. The α, β, γ, and δ isomers may be present in the seed in concentrations that depend on the avocado variety; the α isomer contents range between 30.54 ± 0.37 to 75.57 ± 0.59 mg/100 g, and the β + γ tocopherol have been reported only in the Margarida variety in contents of 9.21 ± 0.43 mg/100g; while the δ form ranges from 8.06 ± 0.37 to 71.55 ± 0.61 mg/100 g (Amado et al. 2019). The sterol β-sitosterol and the triterpene 1,2,4-trihydroxy-nandecane are other valuable compounds reported in seed hexane extracts (Leite et al. 2009).

In the seed and seed coat were identified 83 polar compounds. Among them are organic acids such as citric, quinic, malic, succinic, and isocitric; the perseitol sugar and the terpenoids pentesmide and hydroxyabscisic acid glucoside from the abscisic acid family. Nevertheless, the polyphenolic compounds are the most varied polar molecules, with a total content of 328 to 1303 mg gallic acid equivalents/g dry basis (mg GAE/g d.w.) in this way, the seed can be considered a value-added product (Tables 2, 3, 4).

Seed phenolics are grouped into many classes, such as phenolic acids (hydroxybenzoic and hydroxycinnamic acids), phenolic alcohol derivatives, flavonoids, catechins, and condensed tannins. Additionally, in the seed is found hydroxyphenylacetic acid. In extracts, the epicatechin is the more abundant phenol; although flavonoid concentration also is high around 2.32 mg quercetin equivalents/g (mg QUE/g), it is comparatively lower than that measured in peel and leaves (Figueroa et al. 2018a, Araújo et al. 2020, Rosero et al. 2019, López-Cobo et al. 2016, Figueroa et al. 2018b, Tremocoldi et al. 2018, Oboh, Adelusi, and Akinyemi 2013).

Table 2. Phenolic acids and alcohol derivatives in avocado seed and peel

Phenolic compound	Compound name	Avocado structure	Authors
Phenolic acids			
Hydroxybenzoic acids	4-Hydroxybenzoic acid	Seed, peel	a, b
	Protocatechuic acid	Seed peel	a, b
	Gentisic acid	Seed, peel	a, b
	Benzoic acid	Seed, peel	a, b
	Syringic acid	Seed, peel	a, c
	Vanillic acid	Seed, peel	a, b
Hydroxyphenylacetic acids	3,4-Dihydroxy-phenylacetic acid	Peel	b
Hydroxycinnamic acids	3-O-Caffeoylquinic acid	Seed, peel	a, b, d
	4-O-Caffeoylquinic acid	Seed, peel	a, b, d
	5-O-Caffeoylquinic acid	Seed, peel	a, b, c, e
	3-p-Coumaroylquinic acid	Seed	a
	5-p-Coumaroylquinic acid	Seed	a, d
	4-p-Coumaroylquinic acid	Seed	a
	p-Coumaric acid	Seed, peel	a, b, c
	Caffeic acid	Seed, peel	a, b, c
	Sinapic acid	Seed, peel	c
Methoxycinnamic acids	Ferulic acid	Seed, peel	a, c
	Hydroxyferulic acid	Seed	a
	3-Feruloylquinic acid	Seed	a
	4-Feruloylquinic acid	Seed	a
	Dihydrocaffeic acid	Seed	a
	Ethyl protocatechuate	Seed	a
Phenolic alcohol derivatives	Hydroxytyrosol-glucoside	Seed, peel	a, b, d
	Tyrosol glucoside	Seed, peel	a, b
	Tyrosol-glucosiyl-pentoside	Seed, peel	a, b

[a]Figueroa et al. (2018a), [b]Figueroa et al. (2018b), [c]Rosero et al. (2019), [d]Araujo et al. (2021), [e]Tremocoldi et al. (2018).

Table 3. Flavonoids and catechins in the avocado seed and peel

Phenolic compound	Compound name	Avocado structure	Authors
Flavonoids			
	Quercetin	Seed, peel	a, b, c
	Quercetin-3-β-glucoside	Seed, peel	a, b
	Quercetin-diglucoside (2)	Seed, peel	a, b, c
	Quercetin-O-arabinosyl-glucoside	Peel	a, c
	Quercetin glucoronide	Peel	b
	Multinoside A	Peel	b
	Rutin	Peel	b, c,
	(±)-Naringenin	Seed, peel	a, b
	Kaempferol-O-glucosyl-rhamnoside	Peel	b, c
	Luteolin-7-O-(2”-O-pentosyl) hexoside	Peel	b
	Sukaranetin	Seed	a
Catechins			
	(+)-Catechin	Seed, peel	a, b, c, d, e
	(-)-Epicatechin	Seed, peel	a, b, c, d, e
	(Epi)gallocatechin	Seed	a
	(Epi)catechin glucopyranoside	Seed	a
	(Epi)Catechin gallate	Seed	a, d

[a]Figueroa et al. (2018a), [b]Figueroa et al. (2018b), [c]Rosero et al. (2019), [d]Araujo et al. (2021), [e]Tremocoldi et al. (2018).

Table 4. Condensed tannins and other polar compounds in the avocado seed and peel

Phenolic compound	Compound name	Avocado structure	Authors
Condensed tannins			
Procyanidin dimers	Procyanidins type A dimers (5)	Seed, peel	a, b, c
	Procyanidins type B dimers (11 seed, 7 peel)	Seed, peel	a, b, c, d
Procyanidin trimers	Procyanidin type A trimers (7 seed, 2 peel)	Seed, peel	a, b, c, d
	Procyanidin type B trimers (2)	Seed, peel	a, b, c, d
Procyanidin tetramers	Procyanidin type A tetramers (5)	Seed	a
	Procyanidin type B tetramer	Seed, peel	a
Procyanidin pentamers	Procyanidin type A pentamer	Seed	a
	Procyanidin type B pentamer (2)	Seed	a
Other polar compounds			
	Pyrogallol	Seed	a
	Pyrocatechol	Seed	a
	Vanillin	Seed, peel	a, b, c
	Dihydrocaffeic acid	Peel	b
	Chinchonain I	Peel	b
	Nudiposide	Peel	b
	Flavalignan isomers	Seed	b
	Phlorizin	Seed, peel	c
	Apigenin	Seed, peel	c

[a]Figueroa et al. (2018a), [b]Figueroa et al. (2018b), [c]Rosero et al. (2019), [d]Araujo et al. (2021).

Table 5. Acetogenin content in the avocado fruit (Rodríguez-López, Hernández-Brenes, and de la Garza 2015)

Structure	Acetogenin content* (mg/g fresh basis (f.w.))
Pulp	0.49-9.58
Seed	1.09-8.33
Peel	0.22-12.5

In the avocado seed, specifically in the idioblast oil cells, have been identified acetogenins, molecules derived from fatty acids with a long unsaturated aliphatic chain of 19 to 23 carbons and a highly oxygenated end. Of the purified and studied acetogenins, only 8 structures have been identified: AcO-avocadenyne (seed), AcO-avocadene, an unknown putative acetogenin, persediene, persenone C, persenone A, persin, and persenone B; where persenone A and persenone B are the compounds in the highest concentration (40 and 23%, respectively). The distribution and concentrations of acetogenins widely change according to the avocado fraction (seed, peel, and pulp) and variety (Table 5); however, in Hass avocados, the seed can be 1.6 times more than the pulp (Salinas-Salazar et al. 2017, Rodríguez-López, Hernández-Brenes, and de la Garza 2015).

Peel

The peel is part of the average weight of 8-26% of the fruit, its color and appearance can be light green, dark green, purple or black, and it can present a smooth, rough or lustrous texture; its composition is formed by 37-65% moisture, 2-3.9% protein, 0.9-7% lipids and 13-20% of fiber, 11.3% of carbohydrates, and 0.5% of ash. It is stated that the peel surpasses the fiber content compared with the seed (Bressani, Rodas, and Ruiz 2009, De Sousa Galvão, Narain,

and Nigam 2014, Rotta et al. 2016). The presence of minerals such as calcium, magnesium, potassium, sodium, iron, copper, manganese, and zinc has been reported. Potassium and calcium are the most abundant minerals, and peel can be considered a good source of copper and magnesium (Bressani, Rodas, and Ruiz 2009, Morais et al. 2017),

The main fatty acids in the lipids of the peel in descending order of abundance are oleic ($C_{18:1}$), palmitic ($C_{16:0}$), linoleic ($C_{18:2}$), palmitoleic ($C_{16:1}$), and linolenic ($C_{18:3}$) acids; this order coincides among varieties such as Hass, Quintal, Fortuna, and Margarida. Other minor fatty acids found in the peel are myristic (C_{14}:0), cis-10 heptadecenoic ($C_{17:1}$), stearic ($C_{18:0}$), arachidic ($C_{20:0}$), gadoleic ($C_{20:1}$), behenic ($C_{22:0}$), DHA ($C_{22:6n-3}$), and lignoceric ($C_{24:0}$). As occurs with the seed, the contents vary widely depending on the maturation, variety, and geographical distribution (Table 6). The peel has a similar proportion of SFA, MUFA, and PUFA to that of pulp, which makes them a good source of omega-3 fatty acids (Amado et al. 2019).

Functional molecules with apolar nature as tocopherols reach total contents ranging from 72.94 to 230.7 mg/100 g as the sum of α-, β-, γ-, and δ- forms (Table 7), with higher concentrations than those measured in the seed. It was reported that the predominant tocopherol isomer changes depending on the studied avocado variety (Amado et al. 2019).

Other functional compounds in the peel found in lower amounts than seed and pulp are acetogenins (Table 5); the fractionation to obtain these molecules may show the biological properties reported for acetogenins, although to a lesser extent. In this way, it is possible to propose using peels as a source of bioactive compounds with biological properties beneficial to human health (Rodríguez-Carpena et al. 2011).

Referring polar compounds have been identified 61 in the peel. As in the seed, also are present organic acids (citric, quinic, malic, succinic, and isocitric), perseitol, the terpenoids pentesmide, and hydroxyabscisic acid glucoside Araújo 20 (Figueroa et al. 2018a, Araújo et al. 2020, Rosero et al. 2019, López-Cobo et al. 2016, Figueroa et al. 2018b). Nevertheless, polyphenols are the more varied polar compounds in total contents of 363.8 to 1058.00 mg GAE/g d.w.

Table 6. Content values of the main fatty acids found in the peel lipids (Amado et al. 2019)

Fatty acid	Content (mg/100 g)
Oleic	2283-665.8
Palmitic	1344-485.3
Linoleic	842.2-266.2
Palmitoleic	450.9-78.21
Linolenic	132.5-57.03
Saturated (SFA)	1407-536.5
Monounsaturated (MUFA)	2485-767.7
Polyunsaturated (PUFA)	993.5-335.7

Table 7. Content of tocopherols in the avocado peel (Amado et al. 2019)

Tocopherol isomer	Content (mg/100 g)
α-Tocopherol	75.41-77.28
β+γ-Tocopherol	54.07-89.74
δ-Tocopherol	76.80-82.01

The concentration of phenolic compounds in the peel is higher than in the seed when it comes from raw extracts; however, when the extraction of fractions rich in phenolic compounds is carried out, the seed shows a higher concentration. The polyphenolic compounds reported for the peel (Table 2, 3, 4) are molecules such as hydroxybenzoic acids, hydroxycinnamic acids, flavan-3-ols, catechin and epicatechin, procyanidin dimers, quercetin and some of its glycosylated derivatives, quercetin diglucoside, quercetin 3-O-arabinosyl-glucoside, quercetin 3-O-glucoside, quercetin-3-O-rutinoside, quercetin-3-O-arabinoside, and quercetin 3-O-rhamnoside. Most of the phenols present in peed also are present in the seed, whit the exception of the 3,4-dihydroxy-phenylacetic acid. Procyanidin B_2 and epicatechin have been recognized as the main compounds with significant contributions to antioxidant activity (Tremocoldi et al. 2018, Kosińska et al. 2012, Rosero et al. 2019, Trujillo-Mayol et al. 2021, Bressani, Rodas, and Ruiz 2009, Figueroa et al. 2021, Figueroa et al. 2018b).

Leaves, Branches, and Peduncles

The avocado leaves have lignin, mucilage, fats, starch, and calcium oxalate. Calcium, magnesium, and potassium are in high quantities, followed by phosphorous, sodium, and microelements such as manganese, iron, copper, and zinc (Yamassaki et al. 2017).

Table 8. Phenolic compounds in avocado leaves

Phenolic compound	Compound name	Authors
Phenolic acids		
	Chlorogenic acid	
Flavonoids		
	Quercetin	a
	Quercetin-O-arabinosyl-glucoside	b, c
	Quercetin-3-O-7-rhamnoside	c
	Quercetin-3-O-galactoside	c
	Quercetin-3-O-glucoside	c
	Quercetin-3-O-arabinoside	c
	Quercetin-3-O-rhamnoside	c
	Rutin	a, c
	Kaempferol-3-O-glucoside	c
	Kaempferol-3-O-arabinoside	c
	Kaempferol-3-O-rhamnoside	c
	Tri-glycosylated kaempferol	c
	Luteolin-8-C-glucoside	a, c
Condensed tannins		
Procyanidin trimers	Procyanidin type A trimers (7 seed, 2 peel)	c
	Procyanidin type B trimers (2)	c
Other polar compounds		
	Isorhamnetin	a
	Apigenin	a

[a]Owolabi, Coker, and Jaja (2010), [b]López-Cobo et al. (2016), [c]Yamassaki et al. (2017).

The presence of phenols, alkaloids, cardiac glycosides, saponins, tannins, pigments, and terpenoids brings the leaves the potential to develop nutraceutical products (Lawal et al. 2021). Avocado leaves have higher contents of total phenols (43.82 mg GAE/g) and flavonoids (5.52

mg QUE/g) and a higher radical scavenging ability than the peel, seed, and flesh (Oboh, Adelusi, and Akinyemi 2013). The presence of 19 polyphenolic compounds has been referred outstanding chlorogenic acid, flavonoids, and two procyanidin type B and C trimers (Table 8) (Yamassaki et al. 2017, Owolabi, Coker, and Jaja 2010).

The leaves also contain antioxidant pigments in amounts of 221.81, 318.49, and 36.55 µ/g d.w. for carotenoids, a chlorophyll, and b chlorophyll, respectively. Additionally, water-soluble molecules in the leaves with polysaccharide and glycoconjugate nature have interesting biological effects. The arabinogalactan-protein-rich fraction (FRAGP) of aqueous extracts has been chemically characterized to contain 4.6%, 22.5%, and 76.7% of total protein, arabinogalactan-protein, and carbohydrates, respectively. Arabinose and galactose are the main monosaccharide constituents included in a structure of a type II arabinogalactan (Yamassaki 2013, Yamassaki et al. 2018).

Oil Production Residues

Extracting extra virgin avocado oil by cold pressing leads to a significantly high volume of residues such as pomace, seeds, peels, and wastewater. Those wastes have potential commercial applications in developing conventional, functional, and nutraceutical commodities for human, animal, or agricultural uses (Figure 1). The harvesting time of fruits and the technology used for oil extraction affects the oil yield and the proportion of waste. As seen in Table 9, the proportion of outputs produced changes depending on using a two- or three-phase decanter. In the first case, the oil production is higher, with lower pomace recovery and higher wastewater production. The proximal composition of the wastewater on a wet basis (% w.w.) from a three-phase process consists of 88.3% moisture and 6.3% lipids. 2.6 of dietary fiber, 2.1% ash, 1.2 protein, and 0.1% available carbohydrates; while that of the pomace presents 82.8% of moisture, 1.6% of lipids, 12.4% fiber,1.2% ash, 2.2% protein, and 0.1% of carbohydrates (Permal, Chang, Seale, et al. 2020, Wong, Eyres, and Ravetti 2013).

Table 9. Outputs during avocado cold-pressed oil production using two- or three-phase decanter technology

Technology	Two-phase decanter[a]				Three-phase decanter[b]	
Season	Early		Late		-----	
	Mass (kg)	proportion (%)	Mass (kg)	proportion (%)	Mass (kg)	proportion (%)
Inputs						
Fruit	796		673		1000	
Outputs						
Stone and skin	195	17.1	113	9.4	274	27.5
Pomace	120	10.5	152	12.7	150	15
Oil	73	6.4	129	10.8	75	7.5
Wastewater	750	65.9	805	67.1	448	44.9
Residual water	----	----	----	----	50	5
Total Outputs	1138	99.9	1199	100	997	99.9

[a]Wong, Eyres, and Ravetti (2013), [b]Permal, Chang, Chen, et al. (2020).

Uses of Avocado Byproducts

Seed

Some of the reported uses for avocado seed are found in treating hypertension, diabetes, hypercholesterolemia, and inflammatory conditions, in addition to its use in traditional medicine as antiparasitic, insecticidal, fungicidal, and antimicrobial (Dabas et al. 2013). Seed flour has been shown to significantly lower total cholesterol and LDL-C levels, reducing the prediction of the atherogenic index in a hypercholesterolemic mice model. Protocatechuic acid was the main phenolic compound found in seed flour, followed by kaempferide and vanillic acid (Pahua-Ramos et al. 2012). The long-chain lipids from avocado seed, namely long-chain fatty acids, aliphatic acetogenins, and polyhydroxylated fatty alcohols, are cytotoxic toward Caco-2 cells inducing the caspase-dependent apoptosis and simultaneously inducing arrest of the cell cycle and the modulation of cytokines related to the inflammatory response (Lara-Márquez et al. 2018). Additionally, methanol and hexane seed extracts and their constituents have been proposed as candidates for use as an alternative dengue control agent from their larvicidal effects. It was determined to have higher mortality of the hexane than methanol extract against *Aedes aegypti* since its respective lethal concentration (LC_{50}) were 8.87 and 16.7 mg/mL. The higher mortality of larvae is explained by the presence of β-sitosterol and 1,2,4-trihydroxynonadecane in the extract composition (Leite et al. 2009).

The antioxidant activity of the avocado seed compounds is the main functional property studied. The phenolic compounds (+)-catechin, (-)-epicatechin, kaempferide, rutin, and the chlorogenic, protocatechuic, vanillic, and syringic acids have been targeted as the molecules most contribute to the antioxidant activity. Those antioxidants have shown better protective activity than synthetic ones such as butylated hydroxyanisole (BHA) or butylated hydroxytoluene (BHT) (Moure et al. 2001, Soong and Barlow 2004, Segovia Gómez et al. 2014, Pahua-Ramos et al. 2012).

The evaluation of the avocado seed as a natural antioxidant for meat fat conservation through the prevention of free radicals attacks has been carried out in meat models under chilled storage conditions (4°C). The addition of seed extract (5%) or seed powder (0.1 to 0.5%) almost inhibited meat lipid oxidation (90%) and increased the protein protection by interfering with the formation of carbonyls, also lowered color deterioration by reducing the loss of redness through the retarded metmyoglobin formation. In oil-in-water emulsions of sunflower oil, using concentrations of 0.11% of the seed extract inhibited lipid oxidation by 30% and by 60% when combined with protein (egg albumin), showing a synergistic effect. The main phenolic compounds in the avocado seed that can scavenge free radicals are flavonols, catechins, hydroxycinnamic acids, quercetin glycosides, dimers, and trimers of proanthocyanins; being the condensed tannins the most antioxidant fractions. According to the investigations, the authors consider seed extract a source of antioxidants that decrease the deterioration of valuable compounds, mainly lipids and proteins, and improve the sensory and nutritional quality of meat foods (Segovia Gómez et al. 2014, Rodríguez-Carpena et al. 2011).

The antimicrobial activity of avocado seed extracts has also been studied. The first evaluation of the activity was done in strains of *Staphylococcus aureus, Bacillus subtilis, Aspergillus glaucus, Penicillium notatum,* and *Achromobacter perolens,* then was evaluated the activity of isolated fractions of avocado seed against strains *Micrococcus pyogenes* and

Sarcina lutea (Jensen 1951). The antimicrobial effect against yeasts and fungi of relevance for human and veterinary medicine, such as *Candida parapsilosis, Candida tropicalis, Candida albicans, Candida krusei, Malassezia pachydermatis,* and *Cryptococcus neoformans*, was evaluated too, the maximum concentration used to achieve the minimum inhibitory concentration was 0.65 mg of extract/mL and *Cryptococcus neoformans* was the most sensitive species requiring lower concentration of the extract (Leite et al. 2009). The inhibition of microorganisms commonly found in meat products was evaluated for *Bacillus cereus, Staphylococcus aureus, Listeria monocytogenes, Escherichia coli, Pseudomonas* spp., the mold *Aspergillus niger,* and the yeast *Yarrowia lipolytica*. The results have shown that the seed extracts are more effective against bacteria, being more sensitive those Gram-positive than Gram-negative. The highest inhibitory effect was observed against *B. cereus* and *L. monocytogenes*, whereas for Gram-negative bacteria, the strain *E. coli* was the most sensitive; the mold was found to be the most resistant microorganism and the yeast only showed moderate sensitivity (Rabadán et al. 2017, Rodríguez-Carpena et al. 2011).

Acetogenins are compounds that have shown functional biological activities such as antimicrobial, insecticide, antioxidant, antiplatelet, antithrombotic, and pro-apoptotic (Rodríguez-López, Hernández-Brenes, and de la Garza 2015, Brenes et al. 2019, Rodriguez Saona and Trumble 2000). The antimicrobial effect of isolated molecules of acetogenins has been performed in strains such as *Listeria monocytogenes, Clostridium sporogenes, Bacillus subtillis; Bacillus cereus; Staphylococcus aureus; Salmonella typhi, Shigella dysenteriae, Candida albicans* among others; observing that antibacterial activity increased in parallel with the number of unsaturations of the chain (Rodríguez-Sánchez et al. 2013, Pacheco et al. 2017, Salinas-Salazar et al. 2017, Neeman, Lifshitz, and Kashman 1970, Knapp and Melly 1986). There is a patented avocado seed oil enriched in acetogenins that contain 70% of acetogenins in its composition. AcO-avocadene, persenone, and persin are the main acetogenins at 31%, 28%, and 15% (w.w.), respectively. The product has been classified as a natural antimicrobial agent for ready-to-eat food. Its bactericidal activity was proved against *Listeria monocitogenes* since it is an extract that possesses a lytic effect on cells, showing after 4.3 h, a minimum inhibitory and bactericidal concentrations of 15.6 and 31.2 mg/L, respectively (Salinas-Salazar et al. 2017). This product also is effective against Gram-positive bacteria, with higher efficacy towards spore-formers (*Clostridium sporogenes, C. perfringens, Bacillus subtilis, and Alicyclobacillus acidocaldarius*) and is recommended to substitute or complement common additives used in foods based on milk, meat, or poultry (Villarreal-Lara et al. 2019, IICA 2022).

Obtaining pigments from avocado seeds has been an option for the food industry, which is looking for natural compounds with additional functional activities to their use. The perseoranginine is the pigment present in the avocado seed; it was identified due to the colorful reaction when exposing the avocado seed to oxygen during a cut. This compound results from the reaction catalyzed by the enzyme polyphenol oxidase on the phenolic compounds, leading to the formation of quinones that are red-orange colored compounds (Krokida and Philippopoulos 2005). Its chemical structure belongs to a glycosylated benzotropone with a molecular formula of $C_{29}H_{30}O_{14}$. As the color products form, polyphenol concentration diminishes in a direct relationship; this coloration increases as the pH rises from 2 to 11 but doesn't under a nitrogen atmosphere. Regarding the safety due to the consumption of perseoranginine, it has been tested in mice for 28 days without showing effects of depression, writhing, diarrhea, and hepatotoxicity. The use of this compound as a dye has been suggested

for products stored at low temperatures under an inert atmosphere to preserve the stability of the color (Dabas et al. 2011, Hatzakis et al. 2019, Ozolua et al. 2009).

The treatment of the seed to obtain fiber by chemical methods and the elucidation of its compositional and functional characterization have allowed it to be proposed as a source of dietary fiber. The proximate composition of fiber residue has a protein content of 5%, which even becomes higher than the protein present in the pulp, 2% fat, and crude fiber with variations of 3-24%; the compositional variability may be due to differences in agro-climatic growing conditions of avocado fruit (Barbosa-Martín et al. 2016, Ceballos and Montoya 2013). Avocado seed fiber has considerable water trapping and oil adsorption capacities with uptake values of four or six times the weight of the fiber; therefore, its use is proposed to be used in the formulation of functional foods and the development of commercial applications such as maintenance of freshness, softness, and viscosity in baked products. In addition, based on fiber composition, its use is suggested as a supplement for health problems related to increased intestinal transit, bile acid retention, and cholesterol-lowering (Barbosa-Martín et al. 2016).

The native avocado seed starch granules have an oval shape and an A-type crystallinity pattern, and their solubility increases with temperature. The structure of the native avocado seed starch has been modified to develop technological ingredients for the improvement of the functional properties of viscous foods. Modification through acetylation proceeds by the esterification of the starch hydroxyl groups, replacing the hydroxyl moieties with acetyl groups leading to different degrees of substitution. Starches with a 0.07 degree of substitution yield granules with a round bell shape and C-type pattern, with higher swelling power and solubility at increasing temperatures, displaying reduced breakdown and synergy during freezing and a higher oil absorption than native starch (Silva et al. 2017). Avocado seed starch modification through cross-linking method using sodium tripolyphosphate leads to starch with phosphate group that strengthens the starch chain to prevent viscosity breakdown. Cross-linking using 6% sodium tripolyphosphate during 1 hour of reaction renders the best-modified starch according to moisture and ash content, paste clarity, gel strength, swelling power, solubility, yield, and degree of whiteness. When used in a cream soup, the resulting product had better sensorial acceptance and higher viscosity stability after 5 hours of storage than the product added with native starch or the commercial cream soup (Cornelia and Christianti 2018).

Oil seed extracted with hexane has a high *in vitro* antioxidant activity associated with compounds in its hydrophilic fraction. They show higher anti-inflammatory activity than ibuprofen when administered topically in a paw edema model in Wistar albino rats (Zavala-Guerrero et al. 2020). The biochemical properties of crude avocado seed oil have been studied since they are essential for application into cosmetic commodities such as soap fabrication. The values of refractive index (1.469), specific gravity (0.93 g/cm^3), and peroxide values (1.37 mEq O_2/kg) are very close to those reported for pulp oil; however, saponification value (231.6 mg KOH/g), iodine value (69.4 g I_2/100 g) and acid value (2.06 mg Eq oleic acid/kg) are higher than pulp oil but lower than other unconventional bio-oils such as mango seed, rambutan seed, *M. oleifera*, and pumpkin seed (Wu et al. 2015, Ge et al. 2018, Anwar and Bhanger 2003, Lourith et al. 2016, Rezig et al. 2012).

It is broadly recognized that the waste materials originating from avocado fruit industrialization (seed, peels, and other materials) are an excellent source of bioactive compounds with biological properties such as polyphenolic compounds and their associated antioxidant activity. The transformation of avocado wastes into storable raw materials with high antioxidant properties that may have different food uses has been approached mainly from

drying strategies. Optimization of drying has focused on minimizing the loss of healthy compounds that provide added value to these byproducts taking into account the structural properties and desorption of moisture of the food matrix. In this context, air drying is the most feasible technique for commercial purposes. The drying procedure at a laboratory scale begins with reductions of the raw material to a coarse piece (≤4 x 4 cm), followed by drying (around 40-75°C), grounding into a powder of defined particle size (0.5-0.84 mm), packaging into bags to avoid light, oxygen and moisture exposure, and finally storage (-20°C) (Saavedra et al. 2017, Leite et al. 2009, Pahua-Ramos et al. 2012). During conventional drying at different temperatures (45 to 75°C), air velocities (0.8 to 1.6 m/s) and loading densities (1-3 kg/m^2), it took to the seed 60-75 min to reach the critical moisture and 500-700 min until constant weight. Once dried, the proportions of total phenolic contents (TPC) retained reach 54.89% (Saavedra et al. 2017). The chemical composition of the seed accounts for a higher hygroscopicity than the peels (Saavedra et al. 2017).

Peel

To date, the peel applications are smaller than the seed. Peels from different avocado varieties have been used to obtain oils through hexane extraction with broad perspectives for human consumption. Contrasting peel and pulp oil through their physical and physicochemical characteristics, the first oil displays higher specific gravity and values of acid and saponification but a lower refractive index and peroxide value, which means better oxidative quality (Table 10). Additionally, peel oil has ratios of PUFA/SFA from 0.61 to 1.13, surpassing the minimum of 0.4 necessary to reduce cardiovascular diseases (Bora et al. 2001, Amado et al. 2019).

A functional beverage prepared from sachets of dehydrated avocado peel was developed and analyzed, resulting in a high content of major phenolic compounds standing out of flavonoids, which displayed an antioxidant activity higher than apple tea. The good sensorial acceptability of the infusion and the absence of microbiological contamination in the sachets reinforced the product's commercial potential (Rotta et al. 2016). Another functional beverage made by brewing powdered avocado peel and red ginger in hot water (96°C) proved to possess significant TPC levels, antioxidant activity, and a potential antidiabetic activity, this last from its inhibitory activity of α-amylase enzymes (Putra, Sukesi, and Sulistyadewi 2020).

Table 10. Physicochemical characteristics of peel oils (Bora et al. 2001)

Physicochemical parameter	Range
Specific gravity	0.9116-0.9265
Refractive index	1.4062-1.4467
Acid value (%)	0.98-1.61
Saponification value (g KOH/kg)	200.5-200.9
Iodine value (g I2/100 g)	70.0-71.6
Peroxide value (mEq O2/kg)	1.48-1.7

Indeed, the practical uses of the peel are concentrated more on exploiting the antioxidant activity through the development of complex extracts or the recuperation of purified compounds for the food industry as innocuous additives. Peel extracts have been used for food preservation in porcine meat. Those extracts show limited antimicrobial activity against

Bacillus cereus, Staphylococcus aureus, Listeria monocytogenes, Escherichia coli, Pseudomonas spp., *Yarrowia lipolytica,* and *Aspergillus niger*; however, effectively reduced lipid and protein deterioration, and lowered inconvenient color changes in the meat (Rodríguez-Carpena et al. 2011).

Additionally, they have been assayed as antifungal additives through their incorporation in gelatin and carboxymethylcellulose coatings at a 200 mg/L concentration. The extracts added to the biopolymeric coatings decreased by 45% the proliferation of *Rhizopus stolonifer* and *Aspergillus niger* strains and extended the shelf life for 15 days (Vargas-Torrico et al. 2022). Mixed with nisin (an antimicrobial peptide) maximized the antioxidant and antimicrobial response against *Listeria* when combined in proportions of 39% of nisin and 61% peel. It was seen that the peel has the most potent antioxidant activity than nisin, seed, and their combinations (Calderón-Oliver et al. 2016). Adding a novel peel extract in beef and soy-based burgers in a proportion of 0.5% effectively increased the content of monomeric and oligomeric (epi)catechin and quercetin forms. Also, it reduced lipid and protein oxidation and the presence of urease and carbonic anhydrase activity associated with *Helicobacter pylori* infection (Trujillo-Mayol et al. 2021). Those results were consistent after in vitro digestion, although it reduced the recovery of other phenolic compounds such as catechin, procyanidin B1, procyanidin B2, rutin, and chlorogenic, caffeic, coumaric, and ferulic acids (Trujillo-Mayol et al. 2021).

As in the case of the seed, the drying procedure to condition the peel as a raw material for different uses also includes operations of drying throw convection (45-75 °C) and lyophilization, ground, packaging, and storage (-20 to -80°C) (Trujillo-Mayol et al. 2021, De Sousa Galvão, Narain, and Nigam 2014, Rotta et al. 2016). It has been seen that the peels dry faster than the seeds at different temperatures, air velocities, and loading densities. It takes to the peel 40-50 min to reach the critical moisture and 250-350 min until constant weight. After drying, the peel retains 62.82% of the initial phenolic content (Saavedra et al. 2017), obtaining the highest TPC during drying at 85 °C until a final moisture content of 7%; the most stable compounds are the phenolic acids and procyanidins the more thermolabile ones (Figueroa et al. 2018b).

Leaves, Branches, and Peduncles

As in the case of the peel, the use of leaves is limited; nevertheless, avocado leaves have had an ethnomedical interest since ancient times. Phenolics from the leaves of *Persea americana* have antioxidant activity, which may help prevent the progression of various oxidative stress-related diseases (Owolabi, Coker, and Jaja 2010). Leaf phenolic extracts obtained through hydromethanolic extraction have a protective effect on the pancreas against Fe^2-induced lipid peroxidation in vivo (Oboh, Adelusi, and Akinyemi 2013). It has been proved that the infusions strongly inhibited the herpes simplex virus type 1 (HSV-1), Aujeszky's virus (ADV), and adenovirus type 3 (AD3) in cell cultures, being more active in the mixture of infused substances than the identified compounds alone (De Almeida et al. 1998).

From its numerous health properties, the exploitation of the leaves has focused on the development of functional extracts based on the high antioxidant activity correlated with the polyphenolic, carotenoid, and chlorophyll content. Those studies pretend to increase the preservation of the compounds through conditioning of raw material (drying process), thermal

incubation, and storage of the extract in solution (Yamassaki et al. 2017). The encapsulation of the resulting extracts has also been studied to improve the delivery of target compounds into food and pharmaceutical products; as in the study of Plazola-Jacinto et al. (2019), where the pigments from the *Hass* and *Drymifolia* varieties were extracted using vegetable oils (sunflower and corn oil). In this work, the resulting encapsulates differed in the pigment content depending on the avocado variety used, being the highest in the case of the *Drymifolia* variety; however, the antioxidant activity was higher when assayed the extract of the Hass variety with the corn oil.

Although the biological properties of phenolic fractions of hydroalcoholic leave extracts have attracted the most attention, the arabinogalactan-protein-rich-fraction has been studied since the FRAGP exhibits *in vitro* immunomodulatory properties as an inhibitor of the effect into the classical pathway of the complement system; being the side chains formed mainly by Ara*f* and Gal*p* probably related to the anti-complementary activity of FRAGP (Yamassaki et al. 2018, Yamassaki 2013).

When drying is done to get conditioned raw material, microwaving for 3 min or freeze-drying for 24 h show an insignificant change in TPC; in both cases, the polyphenol oxidase (PPO) and polyphenol peroxidase (POD) enzymes inactivation occurs because of the extremely high or low temperatures used, respectively (Loh and Lim 2018). The air-drying methods are the modalities that most reduce the phenolic content, mainly in chlorogenic acid and rutin levels. At indoor ambient drying conditions (24-26°C, 60% humidity) takes as long as 6 days to attain the final moisture content; while hot air oven drying (40-100°C) lasts from 43.5h (40°C) to 1 h (100°C) to get the constant weight. When hot air is used, temperatures from 40 to 60°C better preserve the TPC and antioxidant activity. Nowadays, the longer the drying times used, the higher the phenolic compounds losses in the air drying modality, mainly due to the enzymatic action (Yamassaki et al. 2017, Loh and Lim 2018). Short blanching pretreatments (1 min) at high temperatures (100°C) have been proved to ensure the inactivation of PPO and POD and the retention of phenolic compounds in avocado leaves, whit minimum leaching (5.6%) into the boiling water (Loh and Lim 2018).

The least studied avocado residues originate from harvest practices and packaging activities, as is the case of branches and peduncles. The nonpolar extracts from those residues and leaves were investigated to delay the maturation of avocado fruits, resulting in no significant effect on firmness or fruit respiratory rate but with an increase in the green color stability (Tochihuitl-Martiñón et al. 2018). To the best of our knowledge, no studies are using the mentioned structures to develop food, pharmaceutical, or cosmetic applications.

Wastewater and Pomace from Oil Production

Biofunctional compounds such as phenolics, carotenes, and tocopherols have been found in both pomace and wastewater, leading to the development of functional ingredients for the preservation of human food. In the case of a spray-dried powder obtained from wastewater, it was added to pork fat and sausages, effectively preventing lipid peroxidation. The effect was comparable to commercial additives such as BHT, BHA, and sodium erythorbate. The powder contained different amounts of α-tocopherol (95.5 to 181.6 mg/kg) and β-carotene (0.7 to 15.1 mg/kg) depending on the carrier material used (Permal, Chang, Chen, et al. 2020). Until now, the use of pomace has been referred to as animal feed (Wong, Eyres, and Ravetti 2013).

Recovery and Protection Technologies of Bioactive Compounds

Extraction Alternatives

The main focus in exploiting avocado residues is undoubtedly the recovery of bioactive compounds from different waste materials to produce phytochemicals used as food, pharmaceutic, or cosmetic ingredients. Avocado byproducts possess interesting biological properties with great potential as a source of ingredients for food, cosmetics, and other industrial fields (Colombo and Papetti 2019).

The methods for obtaining extracts with functional activities have commonly been solvent extraction. For antioxidant and antimicrobial compounds, solvents such as acetone, ethanol, methanol, isopropanol, hexane, diethylether, and water have been used in concentrated or diluted form. In some works, the authors previously grind the raw material to be processed (seed or peel) to reduce the particle size using mill equipment and, in some cases, standardize the particle size (around 40 mesh). The extraction material is processed in a fresh, lyophilized, or dehydrated form in drying ovens at temperatures ranging from 40-50°C and subsequently contacted with the solvent using the reflux method (Soxhlet) or homogenized under conditions of 10-16000 rpm for a few minutes (about 3) or even hours; some works have subsequently used an ultrasound bath to guarantee more penetrability of the solvent in the plant tissue (Pahua-Ramos et al. 2012, Sivanathan and Adikaram 1989, Rodríguez-Sánchez et al. 2013, Segovia Gómez et al. 2014, Rodríguez-López, Hernández-Brenes, and de la Garza 2015, Hatzakis et al. 2019, Rodríguez-Carpena et al. 2011). Experimental designs have been carried out to evaluate the extraction efficiency of bioactive compounds by combining extraction factors such as solvent concentration (26-4%), temperature (20-90°C), and contact time (5-55 min). In those experiments, it was seen that solvent concentrations in the range of 10 to 60% allowed a good compound extraction, while the temperature significantly increased the solubility and diffusion of the molecules without affecting their stability; finally, the contact times did not have a significant effect for the extraction when combined with temperatures that improve the diffusion of the compounds, in a way that contact times of 5 minutes may be sufficient to achieve adequate extraction. However, the combination of variables must be considered essential to achieve extraction optimally; in this way, maceration for hours or even days could be avoided, reducing the extraction time (Segovia Gómez et al. 2014).

Once the homogenization with the solvent has been carried out, the mixture is filtered through filter paper, centrifuged, and the supernatant is lyophilized, or the solvent is evaporated to dryness at 40-80°C under vacuum using a rotary evaporator or under nitrogen (Pahua-Ramos et al. 2012, Rodríguez-López, Hernández-Brenes, and de la Garza 2015, Hatzakis et al. 2019, Raymond Chia and Dykes 2010, Salinas-Salazar et al. 2017, Rodríguez-Carpena et al. 2011).

The recovery of high-value compounds from agricultural byproducts has become a relevant topic, in which many studies have focused on their extraction strategies. Conventional extraction, such as maceration, liquid-liquid, and Soxhlet, has been mainly used in high-value compounds' industrial processes. For instance, Ferreira, Falé, and Santos (2022) studied the ethanolic extract of avocado peels for their antioxidant and antibacterial properties against the *Staphylococcus* family. The phenolic-rich extracts were further incorporated in emulsions to develop cosmetic formulations as a strategy to generate antimicrobial and antioxidant agents. However, several limitations are still to be solved for its industrial processing, such as large

amounts of organic solvents, considerable time, and thermal degradation of phenolic compounds. Novel technologies have emerged to reduce these limitations and enhance the extraction and stability of phenolic compounds. Green technologies such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and pressurized liquid extraction have been studied to increase thermal efficacy and selectivity and reduce extraction times and solvent consumption. Rodríguez-Martínez et al. (2021) applied the UAE to optimize the extraction of phenolic compounds from avocado peels. The ethanolic extract obtained presented flavanols, flavonols, flavones, flavanones, and mainly phenolic acids. It proved to be a sustainable extraction technique as it considerably reduces the amount of organic solvent and time compared to conventional extraction.

Similarly, Monzón et al. (2021) used a response surface methodology and artificial neural network to optimize the UAE conditions from avocado seed and peel. This study represents an efficient, economical, and ecological strategy for extracting phenolic compounds from avocado residues. Furthermore, the MAE has also been studied as a green alternative to extracting phenolic compounds from avocado peels (Araujo et al. 2021). The fiber-bonded phenolics obtained (phenolic acids mainly) exhibited higher antioxidant activity compared to conventional extraction. Figueroa et al. (2021) optimized the extraction of bioactive polyphenols from avocado peel using MAE in another study; this avocado peel MAE extract exhibited higher matrix metalloproteinases inhibitory and antioxidant capacities, making it suitable for applications in the food industry. Multiple studies have reported the optimization process using a different solvent with MAE technology to obtain fiber-bonded phenolic acids from avocado seeds (Araujo et al. 2021, Weremfo, Adulley, and Adarkwah-Yiadom 2020). MAE technology exhibited advantages over conventional extraction methods regarding extraction efficiency and antioxidant activity. Finally, Mazyan et al. (2021) studied the optimum extraction of phenolics from avocado fruit flesh (*Persea americana*) using subcritical water extraction. The authors concluded that extracting with subcritical water enhances the phenolic compounds extraction yields.

Protection and Delivery Technologies

The residues of the avocado fruit derived from the pharmaceutical and food industry consist mainly of peel and seeds and, to a minor extent, leaves, branches, wastewater, and pomace. Those residues have in their composition phytochemical compounds with numerous biological activities, among which are anti-inflammatory, antimicrobial, antidiabetic, antihypertensive, anticancer, and antioxidant; however, these compounds are unstable and sensitive to different environmental conditions, so their concentration and activities may be reduced during processing, storage and shelf life (Brai et al. 2020, Cheikhyoussef and Cheikhyoussef 2022).

Once extracted, an alternative to avoid damage to the compounds of interest is encapsulation; this strategy provides an improvement in physicochemical stability, controlled release, bioavailability, and extending shelf life for long periods due to the formation of a cover that brings protection against oxygen, light, moisture, and other undesirable interactions (Nguyen et al. 2021). The encapsulation of these compounds facilitates their application into different systems that could be used to formulate products, mainly in the food and pharmaceutical sectors. The available encapsulation methods and systems are numerous; some include forming and stabilizing emulsions and using biopolymers for inclusion in gel or